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RESEARCH MEMORANDUM

INVESTIGATION OF A THIN WING OF ASPECT RATIO 4 IN THE AMES 12-FOOT PRESSURE WIND TUNNEL.

I - CHARACTERISTICS OF A PLAIN WING

By Ben H. Johnson, Jr.

Ames Aeronautical Laboratory
Moffett Field, Calif.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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SUMMARY

Wind-tunnel tests have been made of a semispan model of an unswept wing of aspect ratio 4 and taper ratio 0.5 at Mach numbers up to 0.94 to determine its aerodynamic characteristics as influenced by Mach number, Reynolds number, and modification of the basic diamond profile by rounding the ridge. The basic diamond profile had a maximum thickness of 4.5 percent of the chord.

Lift, drag, and pitching-moment data are presented for Reynolds numbers from 2,000,000 to 10,190,000 at a Mach number of 0.20 and for Mach numbers from 0.20 to 0.94 at constant Reynolds numbers of 3,000,000, 2,730,000, 2,000,000, and 1,000,000.

The data presented herein indicated no severe static-longitudinal-stability problems up to a Mach number of 0.94. There was a marked rearward movement of the aerodynamic center at a lift coefficient of approximately 0.4. Increasing the Mach number reduced the lift coefficient at which this movement started. At zero lift, the total movement of the aerodynamic center with Mach number was only about 7 percent of the mean aerodynamic chord. There was an increase of 50 percent in the lift-curve slope with increasing Mach number up to a Mach number of 0.90. The lift-curve slope decreased at higher Mach numbers. The Mach number for drag divergence was indicated to be about 0.85, the minimum drag increasing 100 percent between this Mach number and 0.94.

At constant Mach number, the data indicate no appreciable effect of dynamic scale at Reynolds numbers greater than 2,500,000. At lower Reynolds numbers with the basic diamond profile, there were hysteresis effects in the pitching-moment curves near zero lift which have been attributed to laminar separation in the proximity of the

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line of maximum thickness. Rounding this ridge for a distance of 0.15 chord eliminated these effects at Reynolds numbers down to 1,000,000. Rounding the ridge also decreased the minimum drag at high Mach numbers and increased the maximum lift-drag ratio approximately 10 percent, but had little effect upon the lift characteristics.

INTRODUCTION

The present rapid development of airplanes and missiles which are expected to fly at Mach numbers of 2.0 and above has focused increasing attention on the characteristics of unswept wings with sharp-edged profiles. At these Mach numbers, wing sweep, which is beneficial in delaying the effects of compressibility as long as the wing is swept behind the Mach angle, is no longer structurally feasible due to the large amount of sweep requisite to the attainment of subcritical flow over the wing. A sharply pointed triangular plan form is structurally feasible, but the low value of lift-curve slope resulting from the extremely small aspect ratio is undesirable if high wing loadings are to be employed.

In order to evaluate the compressibility effects at Mach numbers up to 0.94, a straight wing of aspect ratio 4 and taper ratio 0.5 has been tested in the 12-foot pressure wind tunnel. The basic wing profile was a symmetrical double wedge with a maximum thickness of 4.5 percent of the chord. In addition to the tests at high Mach numbers, the effect of dynamic scale was investigated at low speeds at Reynolds numbers up to 10,000,000.

SYMBOLS

The following symbols are used in this report:

C_L lift coefficient $\left(\frac{\text{lift}}{qS}\right)$

C_D drag coefficient $\left(\frac{\text{drag}}{qS}\right)$

C_m pitching-moment coefficient about quarter-chord point of the wing mean aerodynamic chord $\left(\frac{\text{pitching-moment}}{qSc'}\right)$

[redacted]

M Mach number $\left(\frac{V}{a}\right)$

[redacted]

R Reynolds number $\left(\frac{\rho V c'}{\mu}\right)$

$C_{D_{min}}$ minimum drag coefficient

C_{L_α} lift-curve slope $\left(\frac{\partial C_L}{\partial \alpha}\right)$

α angle of attack of wing-chord plane, degrees

δ^* displacement thickness of boundary layer $\left[\int_0^\delta \left(1-\frac{u}{V}\right)dy\right]$

where

S wing area, square feet

c' wing mean aerodynamic chord, chord through centroid of wing semispan plan form, feet

c local chord, feet

q dynamic pressure, pounds per square foot $\left(\frac{1}{2}\rho V^2\right)$

ρ mass density of air, slugs per cubic foot

u local velocity in tunnel-wall boundary layer, feet per second

V free-stream velocity, feet per second

μ viscosity of air, slugs per foot-second

a speed of sound, feet per second

δ tunnel-wall boundary-layer thickness, inches

y perpendicular distance from tunnel wall, inches

MODEL AND APPARATUS

The tests were conducted in the Ames 12-foot pressure wind tunnel which is a closed-throat, variable-density wind tunnel with a low turbulence level closely approaching that of free air. The test section, which has a nominal diameter of 12 feet, has been modified by the addition of four equally spaced flat sections of 4-foot chord.

Sufficient power is available to choke the tunnel at all pressures less than 0.47 atmospheres, providing Reynolds numbers at choking up to 1,900,000 per foot. The density of the air in the tunnel is continuously variable from 1/6 to 6 times atmospheric density, permitting independent variation of Reynolds number and Mach number.

A semispan model representing a wing of aspect ratio 4 and taper ratio 0.5 was used in this investigation. The 50-percent-chord line of the wing was normal to the free stream, and the basic airfoil profile was a symmetrical double wedge with a maximum thickness of 4.5 percent of the chord at 50 percent of the chord. The model was constructed of solid steel and had a root chord of 2 feet and a semispan of 3 feet, as shown in figure 1. The model was equipped with constant-chord leading-edge and trailing-edge plain flaps which remained undeflected throughout the tests reported herein. The gaps between the flaps and the wing were 0.015 inch and unless otherwise specified were unsealed.

In addition to tests of the wing with the basic diamond profile, tests were conducted with the ridge rounded for a distance of 15 percent of the local chord. Rounding of the ridge was necessarily accompanied by a decrease in wing thickness ratio from 0.045 to 0.042. These two wing profiles, hereinafter referred to as the sharp-ridge profile and the round-ridge profile, are shown in figure 1.

The semispan model was mounted vertically in the wind tunnel, the tunnel floor serving as a reflection plane. A photograph of the model installation is shown in figure 2.

The turntable upon which the model was mounted was connected directly to the force-measuring apparatus. No attempt was made to remove the tunnel boundary layer which, at the location of the model, had a displacement thickness δ^* of 0.5 inch.

CORRECTIONS TO DATA

The data have been corrected for the effects of tunnel-wall interference, constriction due to the tunnel walls, and model-support tare forces.

The method of reference 1 has been used in correcting the data for tunnel-wall interference. The following corrections were added:

$$\Delta\alpha = 0.363\ C_L$$

$$\Delta C_D = 0.0056\ C_L^2$$

$$\Delta C_m = 0$$

Corrections to the data for the constriction effects of the tunnel walls have been evaluated by the method of reference 2. The magnitude of these corrections as applied to the Mach number and to the dynamic pressure (measured with the wind tunnel empty) is illustrated by the following table:

Corrected Mach number	Uncorrected Mach number	$\frac{q,\text{corrected}}{q,\text{uncorrected}}$
0.95	0.937	1.051
.93	.923	1.040
.90	.897	1.028
.87	.868	1.021
.85	.848	1.017
.80	.799	1.012
.70	.700	1.008
.60	.600	1.006
.50	.500	1.005
.30	.300	1.000

Tare corrections due to the air forces exerted on the exposed area of the turntable have been applied to the drag data. These corrections were obtained from measurements made with the model removed from the tunnel. No attempt has been made to evaluate the interference effects between the model and the turntable. The magnitude of the measured drag tares varied with Reynolds number and had the following values based on the wing area:

Reynolds number	C_D Tare
1,000,000	0.0072
2,000,000	.0063
3,000,000	.0059
6,000,000	.0057
10,000,000	.0056

TESTS

Lift, drag, and pitching-moment data have been obtained as a function of angle of attack for both wing profiles. The angle-of-attack range was limited at high Mach numbers by tunnel power and model strength. For the sharp-ridge profile, data were obtained for Mach numbers up to 0.94 and Reynolds numbers from 750,000 to 3,000,000. At a Mach number of 0.20, data were obtained to a Reynolds number of 10,190,000. For the round-ridge profile, data were obtained over a range of Mach numbers up to 0.94 and a range of Reynolds numbers from 1,000,000 to 2,730,000. Data were also obtained on the sharp-ridge profile with transition fixed on both the upper and the lower surfaces by 1/4-inch strips of number 60 carborundum grains at two different chordwise positions. These two positions were:

1. Along a line parallel to and 1-11/16 inches aft of the leading edge (14 percent of the tip chord and 7 percent of the root chord)

2. Along the 40-percent-chord line

RESULTS

The effects of Mach number on the aerodynamic characteristics of the wing with the sharp-ridge profile are presented for various Mach numbers up to 0.94 in figures 3 and 4 for constant Reynolds numbers of 3,000,000 and 2,000,000. The effects of Reynolds number and fixed transition are presented in figures 5, 6, 7, and 8 for constant Mach numbers of 0.20, 0.50, 0.80, and 0.90. The effects of Mach number on the aerodynamic characteristics of the wing with the round-ridge profile are presented at various Mach numbers up to 0.94 in figures 9, 10, and 11 for constant Reynolds numbers of 2,730,000, 2,000,000, and 1,000,000. From these data, independent effects of Mach number, Reynolds number, and wing profile may be evaluated.

DISCUSSION

The Effects of Mach Number

The variation of lift-curve slope with Mach number is presented in figure 12. These data indicate an increase in C_{L_α} with increasing Mach number to a maximum, at a Mach number of 0.90, approximately 50 percent greater than the low-speed value. At higher Mach numbers, there is a decrease in the slope. These compressibility effects are characteristic of unswept wings. The high value of the Mach number for lift divergence is a direct consequence of the small wing thickness and the low-aspect ratio. The values of C_{L_α} at high Mach numbers are considerably less than the theoretical values indicated by reference 3. The lift curves of figures 3 through 11 indicate low maximum lift coefficients, and a gentle stall.

The pitching-moment curves of figures 3 through 11 indicate a marked rearward movement of the aerodynamic center at a lift coefficient of approximately 0.4. The lift coefficient at which this movement began generally decreased with increasing Mach number. The hysteresis indicated by the moment curves of figures 4, 6, 7, and 8 will be discussed later.

The effect of Mach number on the location of the aerodynamic center at zero lift is shown in figure 13. These data indicate a slight forward movement of the aerodynamic center with increasing Mach number to a maximum forward position of 22 percent of the mean aerodynamic chord at a Mach number of 0.85. Between Mach numbers of 0.85 and 0.90 the aerodynamic center moved aft, but at higher Mach numbers a forward movement is again indicated. The total movement of the aerodynamic center between Mach numbers of 0.2 and 0.94 was only about 7 percent of the mean aerodynamic chord. Examination of the pitching-moment curves of figures 3 through 7 reveals that at low lift coefficients they become nonlinear at Mach numbers above about 0.80. It thus becomes difficult to establish the location of the aerodynamic center at these high speeds. However, for nonlinear moment curves, the location of the zero-lift aerodynamic center is no longer representative of the stability characteristics of the wing.

The effect of Mach number on the minimum drag coefficient is presented in figure 14. These data indicate a sizeable increase in minimum drag for Mach numbers above 0.85. As discussed in reference 4, the indicated Mach number for drag divergence may be low due to the fact that the effect of Mach number on the interference drag between the model and the turntable was neglected in the evaluation of the drag tares. The value of minimum drag increased 100 percent as the Mach number increased from 0.85 to 0.94. The drag curves of figures 3 through 11 indicate a decrease, with increasing Mach number, in the rate of change of drag with lift.

The Effect of Reynolds Number and Transition Strips

In figure 5, data are presented for Reynolds numbers of 2,000,000, 5,720,000, and 10,190,000 at a constant Mach number of 0.20. These data indicate that for the wing with a sharp ridge there is little effect of Reynolds number at low Mach numbers. The data of figures 6, 7, and 8, however, indicate considerable hysteresis in the pitching moments at low Reynolds numbers for constant Mach numbers of 0.50, 0.80, and 0.90. These effects were eliminated by fixing the transition on the wing and also by increasing the Reynolds number with the transition free. The minimum Reynolds number, at which the hysteresis was no longer apparent, increases with increasing Mach number. From these observations, it is deduced that this effect may be associated with laminar separation, and the fact that transition strips were effective as far aft as 40 percent of the chord indicates that separation was taking place in the vicinity of the sharp ridge. The adverse pressure gradient immediately aft of the ridge is large for this profile and it is not difficult to conceive of laminar-boundary-layer separation taking place at this ridge, even at zero lift.

It is observed that the lift was little affected by either the changes in Reynolds number or the fixing of transition. It may also be noted that there was no consistent effect of change in Reynolds number upon the minimum drag.

The Effect of Wing Profile

On the hypothesis that reduction of the adverse pressure gradient in the proximity of the ridge would alleviate the laminar separation occurring at low Reynolds numbers, the ridge of the wing was rounded. That the substitution of a round ridge in place of a sharp ridge was effective in preventing laminar separation is evident from comparison of the pitching-moment curves of figures 10 and 11 with those of figures 6, 7, and 8. Since the rounding of the ridge necessarily caused a reduction in the thickness ratio, it is to be expected that the compressibility effects would differ slightly for the two airfoil profiles. The variations of the lift-curve slope with Mach number (fig. 12) indicate a slight decrease in the peak value for the thinner section. The variations of minimum drag with Mach number (fig. 14) show that thinning the section slightly increased the Mach number for drag divergence, and decreased the rate of drag rise with Mach number. The minimum drag at low Mach numbers was substantially the same for both profiles. A comparison of the lift-drag ratios (fig. 15) indicates an increase in the maximum lift-drag ratio of about 10 percent from rounding the ridge. These salutary effects on the drag are probably due to a combination of reduced thickness and an alleviation of the adverse pressure gradient at the ridge line.

It is of interest to note that, for a given load, the maximum bending stress for a solid wing with the round ridge is less than for a wing with the sharp ridge due to an increase in the section modulus.

CONCLUSIONS

The following conclusions have been drawn from the results of tests of the thin unswept wing with the diamond profile:

1. At a Mach number of 0.90, the lift-curve slope had increased to a maximum, approximately 50 percent greater than the low-speed value.

2. There was a marked rearward movement of the aerodynamic center at lift coefficients of approximately 0.4. The lift coefficient at which the movement began generally decreased with increasing Mach number.

3. At zero lift, the total movement of the aerodynamic center due to compressibility was approximately 7 percent of the mean aerodynamic chord, the maximum forward location being 22 percent of the mean aerodynamic chord at a Mach number of 0.80.

4. The Mach number for drag divergence was approximately 0.85. The value of minimum drag increased 100 percent as the Mach number increased from 0.85 to 0.94.

5. The rate of rise of drag with lift decreased with increasing Mach number.

6. Above a Reynolds number of 2,500,000, there was no measured effect of dynamic scale.

7. At low Reynolds numbers, hysteresis of the pitching moment was observed. This hysteresis is attributed to laminar separation at the sharp ridge on the diamond airfoil section. The minimum Reynolds number for alleviation of these effects increased with increasing Mach number.

8. Modification of the airfoil profile by rounding the ridge eliminated the hysteresis in the pitching moment at all Mach numbers for Reynolds numbers as low as 1,000,000. This minor profile modification also decreased the minimum drag at high Mach numbers and increased the maximum lift-drag ratio approximately

10 percent, but had little effect upon the lift characteristics.

Ames Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Moffett Field, Calif.

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2. Herriot, John G.: Blockage Corrections for Three-Dimensional-Flow Closed-Throat Wind Tunnels, with Consideration of the Effect of Compressibility. NACA RM No. A7B28, 1947.

3. Young, A. D.: Note on the effect of compressibility on the lift curve slope of a wing of finite span. TN No. Aero. 1250 (HST), R.A.E., 1943.

4. Edwards, George G., and Stephenson, Jack D.: Tests of a Triangular Wing of Aspect Ratio 2 in the Ames 12-Foot Pressure Wind Tunnel. I – The Effect of Reynolds Number and Mach Number on the Aerodynamic Characteristics of the Wing with Flap Undeflected. NACA RM No. A7K05, 1948.

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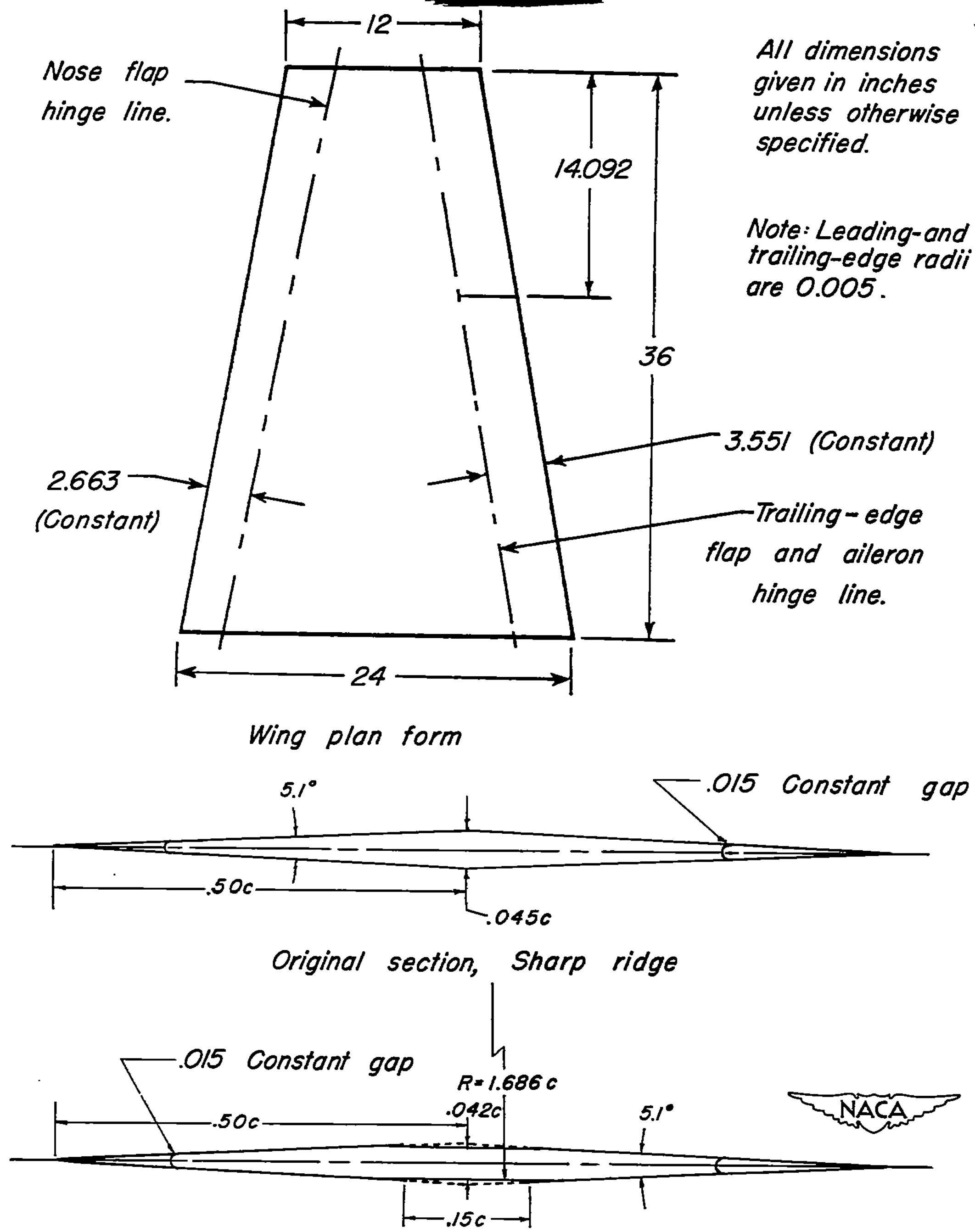

Figure 1.-Semispan model of a wing of aspect ratio 4, tested in the 12-foot pressure wind tunnel.

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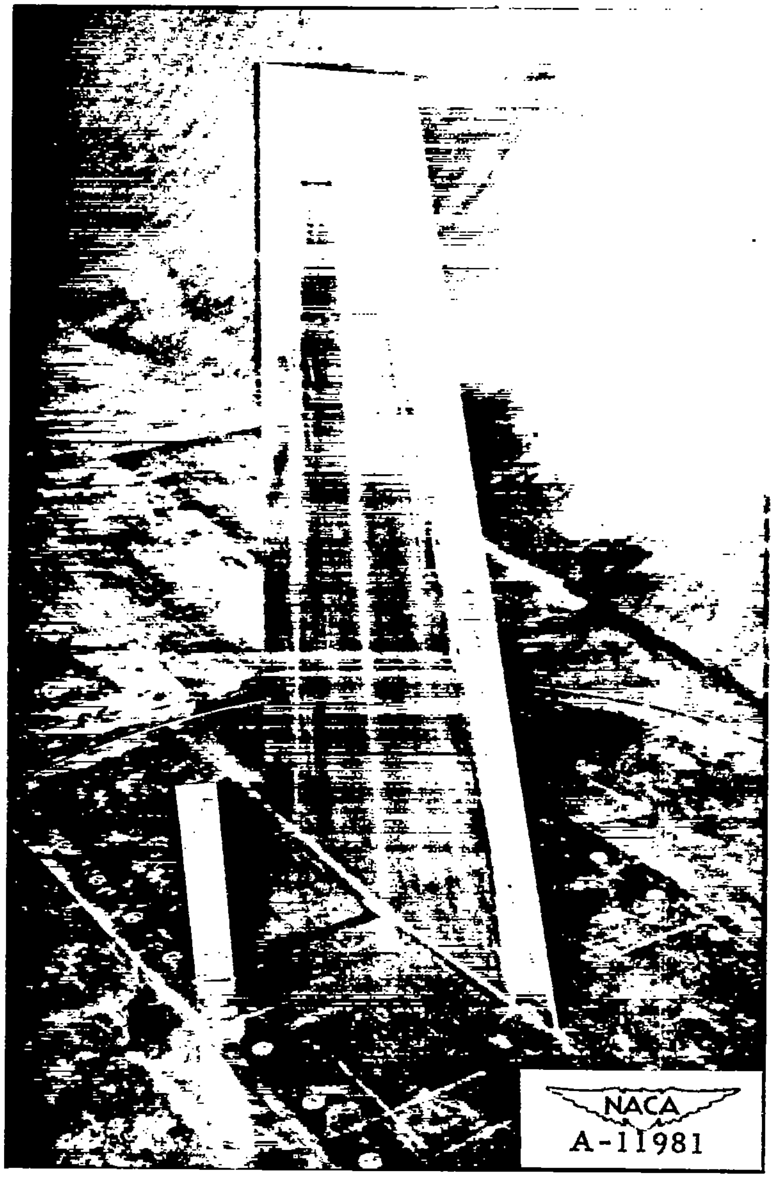

Figure 2.- Semispan model of a wing of aspect ratio 4 mounted in the 12-foot pressure wind tunnel.

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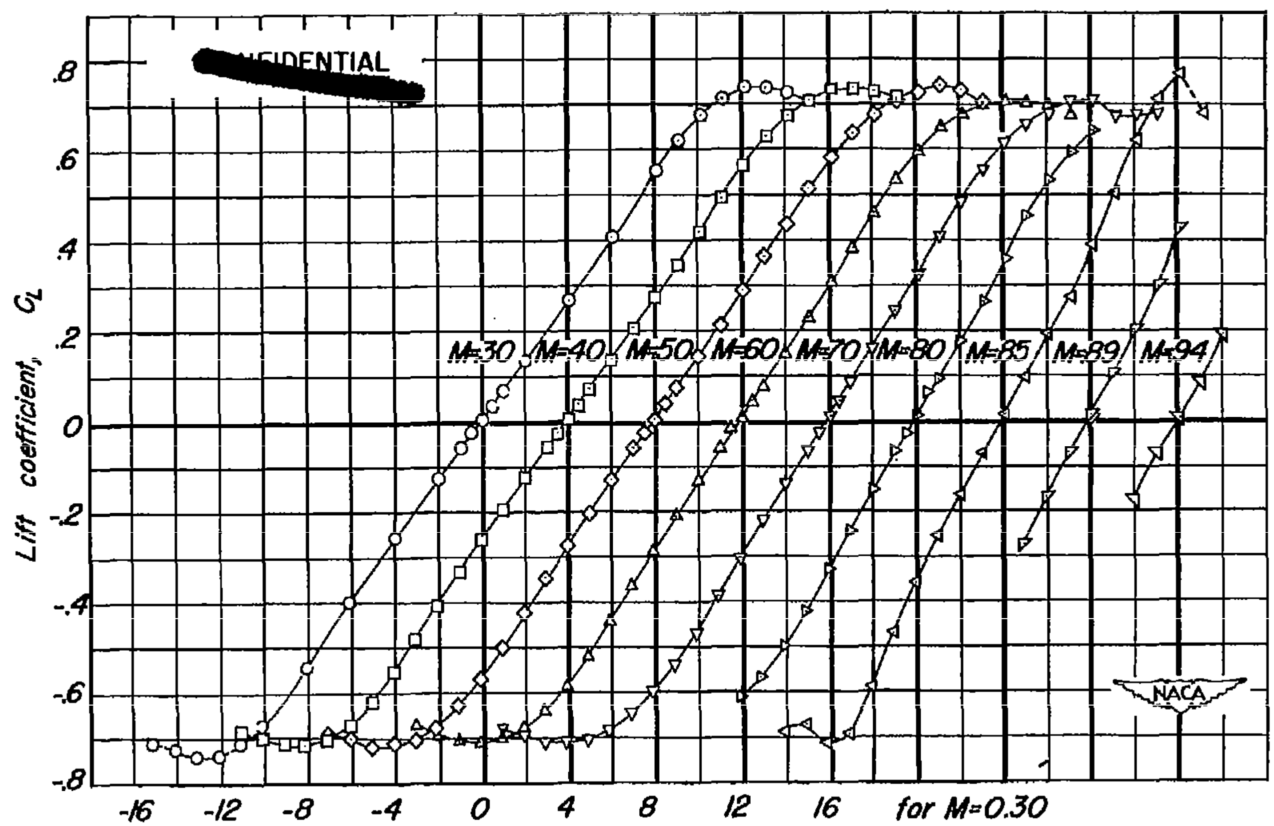

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(a) C_L vs α

Figure 3.- The effect of Mach n[redacted] *aerodynamic characteristics of the wing with the sharp ridge profile. R, 3,000,000.*

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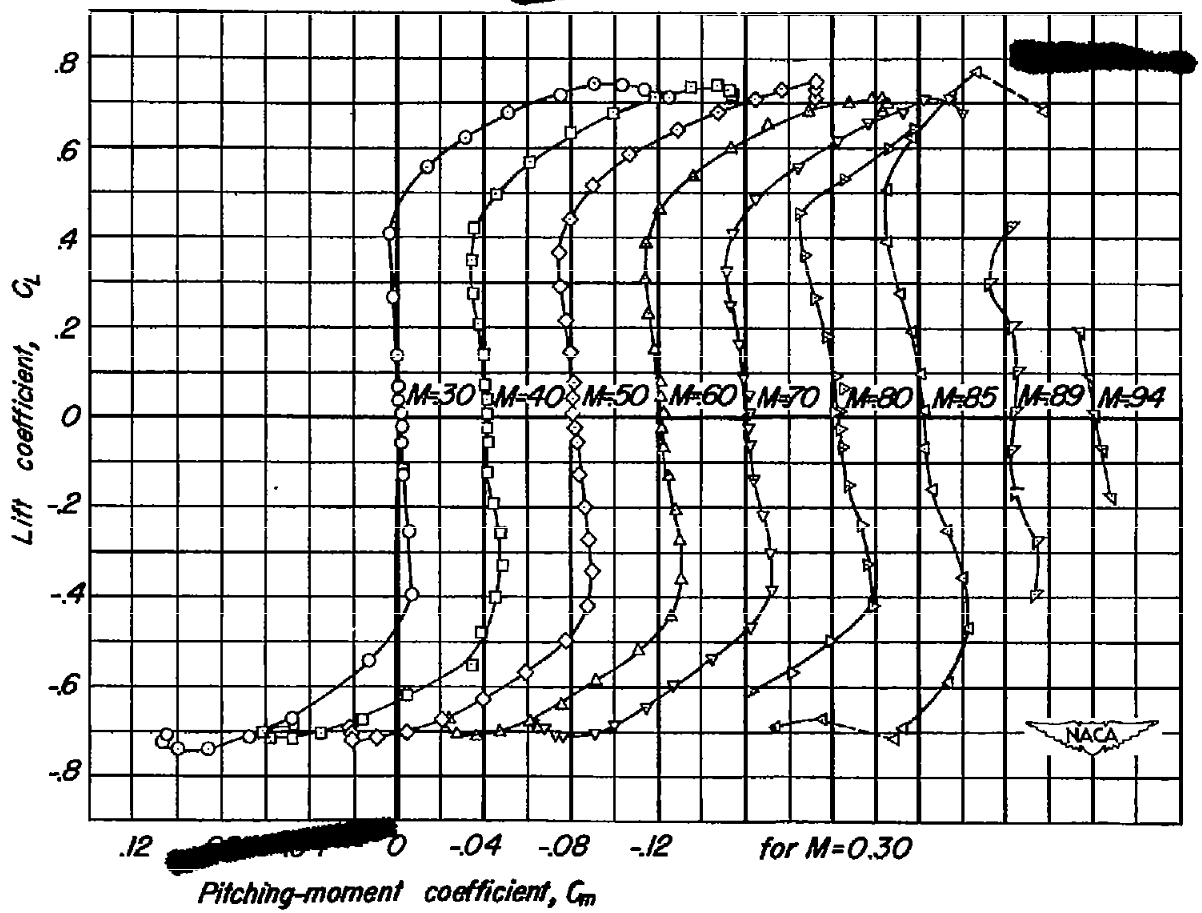

(b) C_m vs C_L

Figure 3.-Continued.

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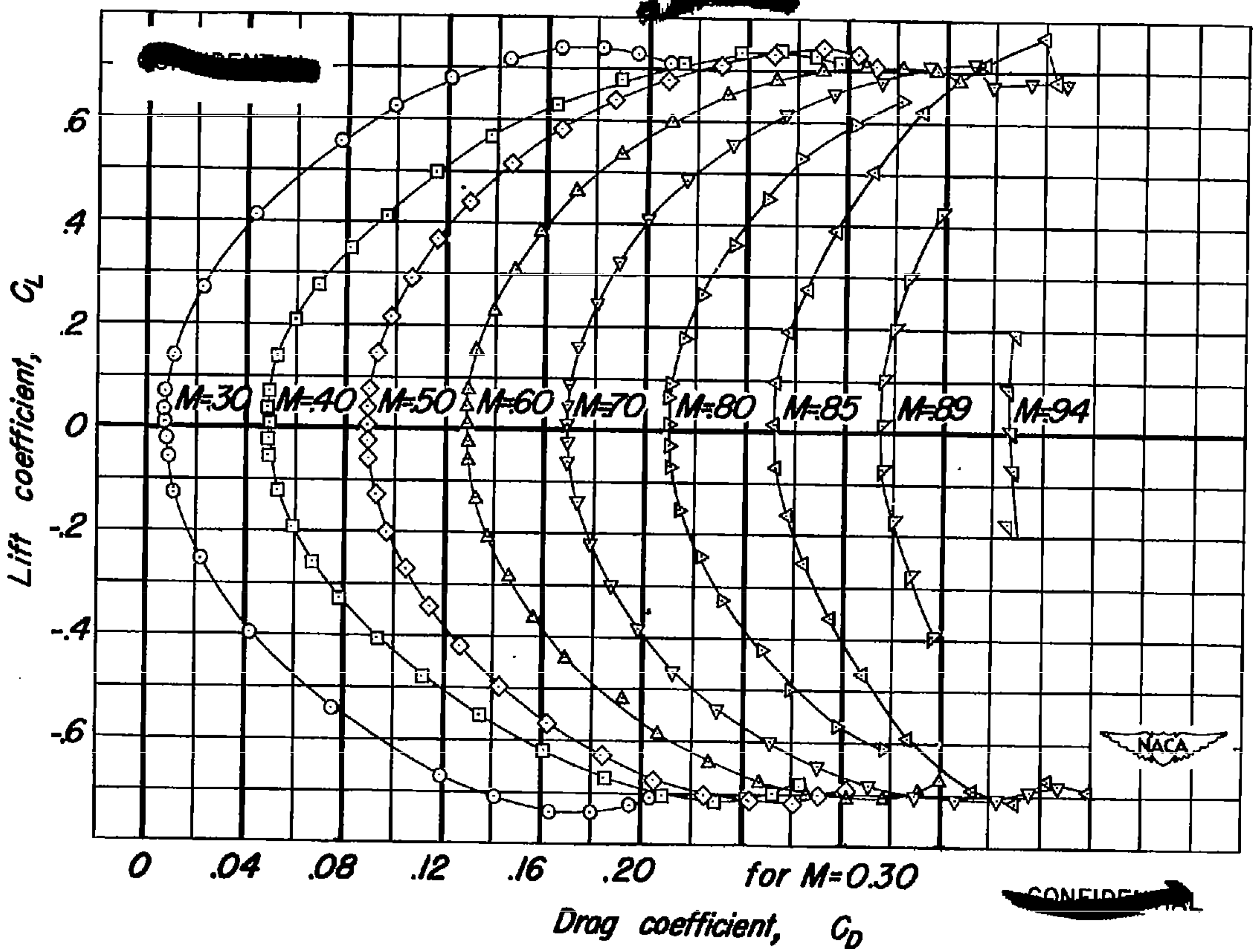

(c) C_D vs C_L

Figure 3.-Concluded.

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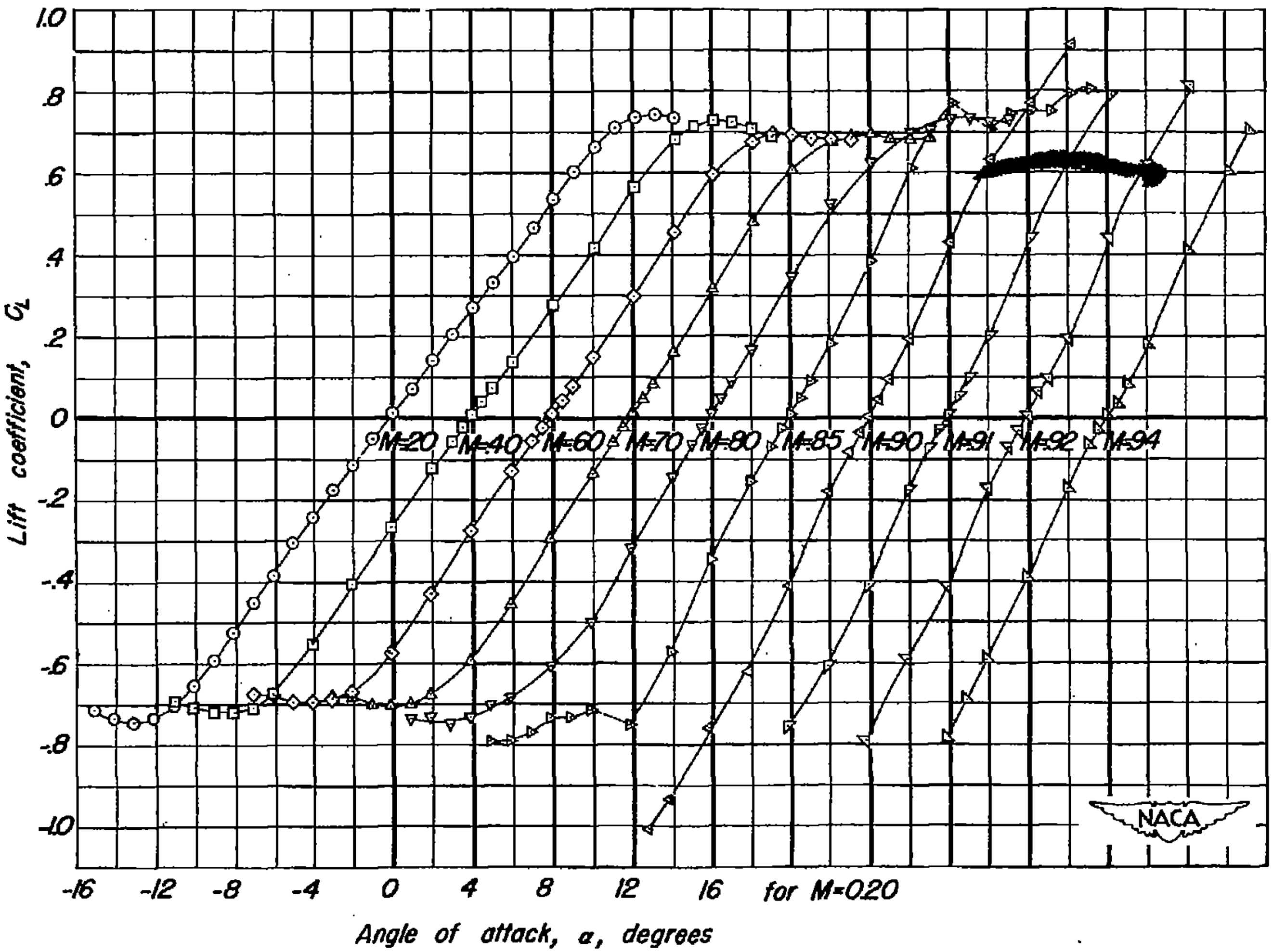

(a) C_L vs α

Figure [redacted] effect of Mach number on the aerodynamic characteristics of the wing with the sharp ridge profile. R, 2,000,000.

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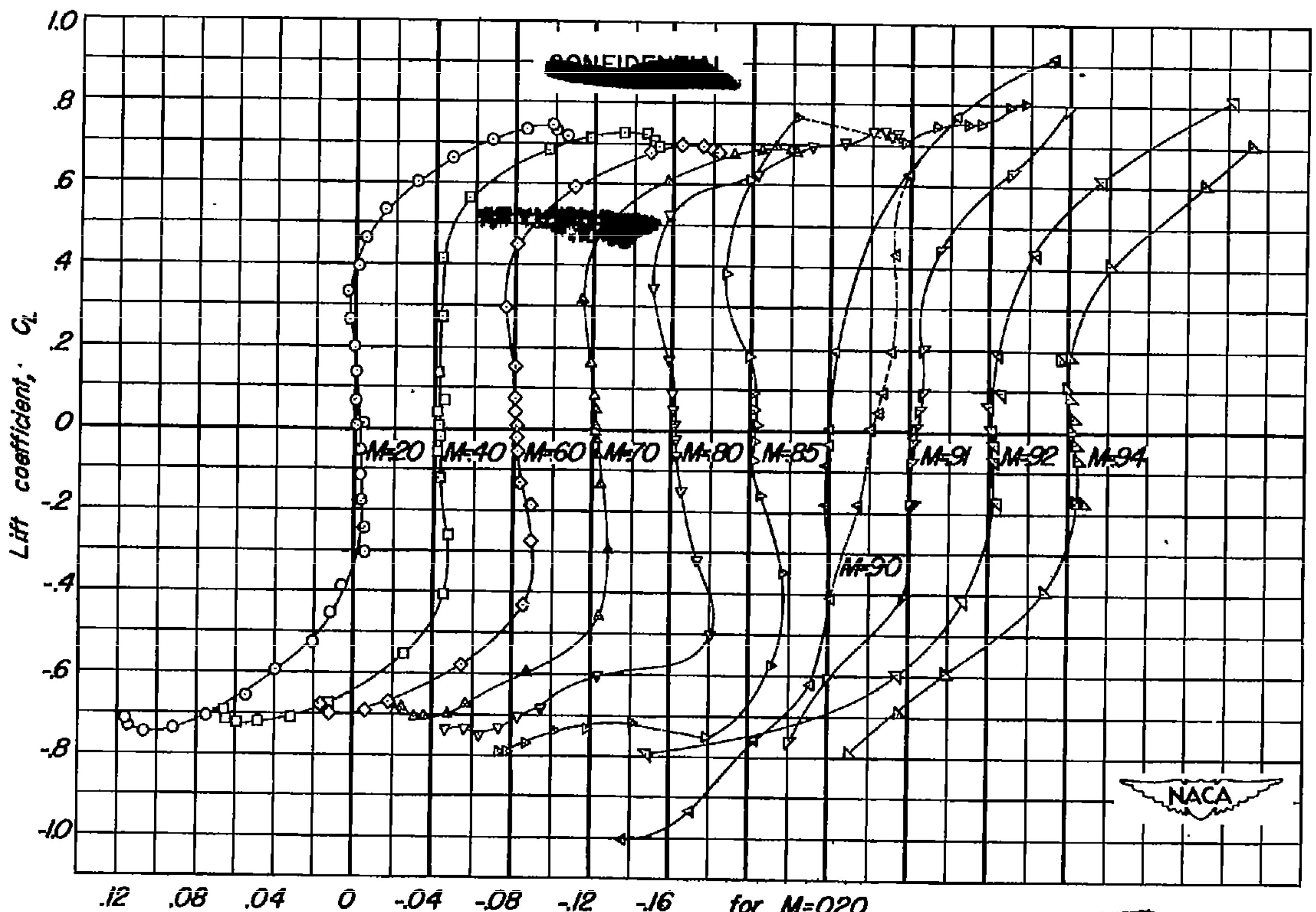

Pitching-moment coefficient, C_m

(b) C_m vs C_L

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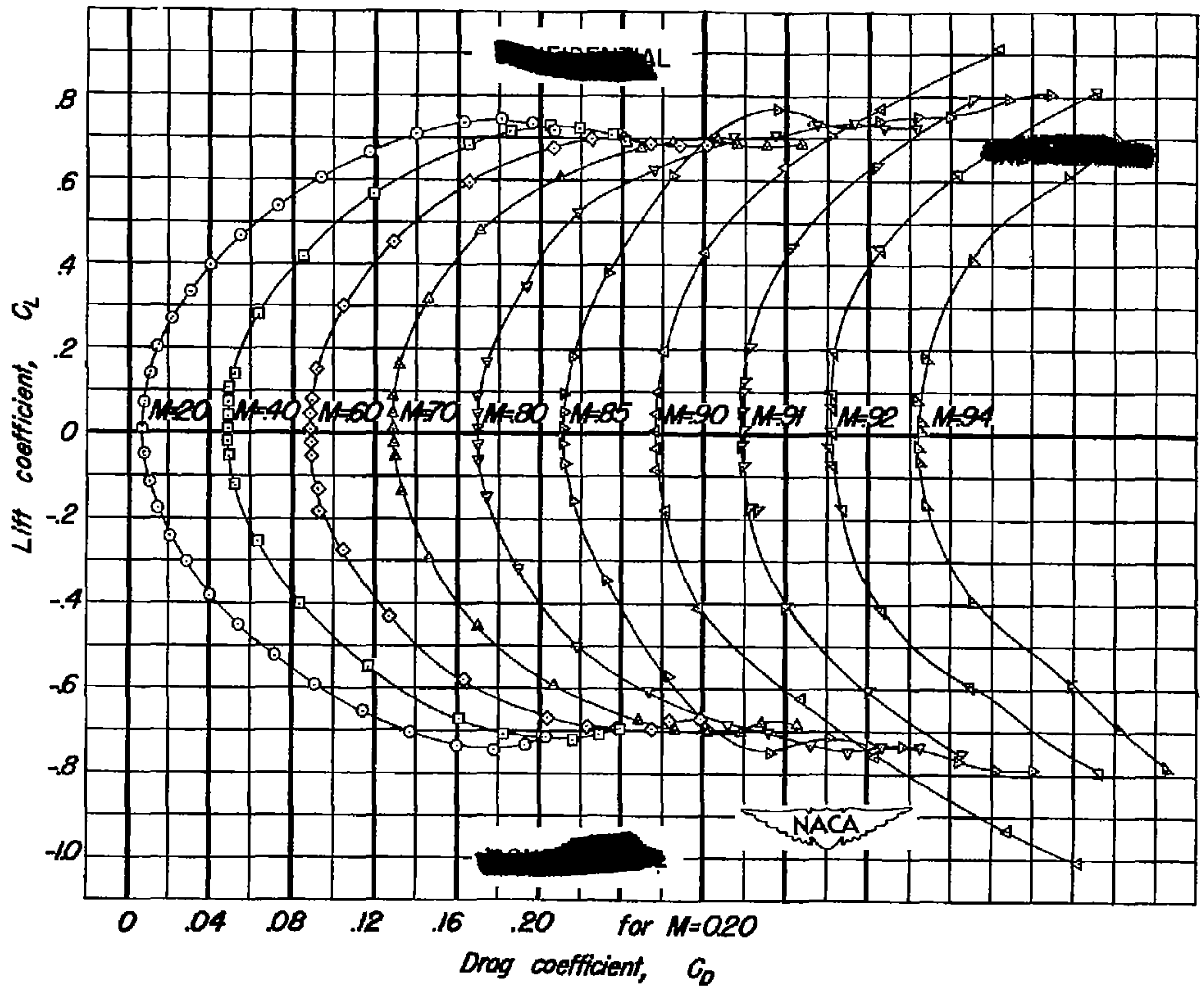

(c) [redacted]

Figure 4.-Concluded

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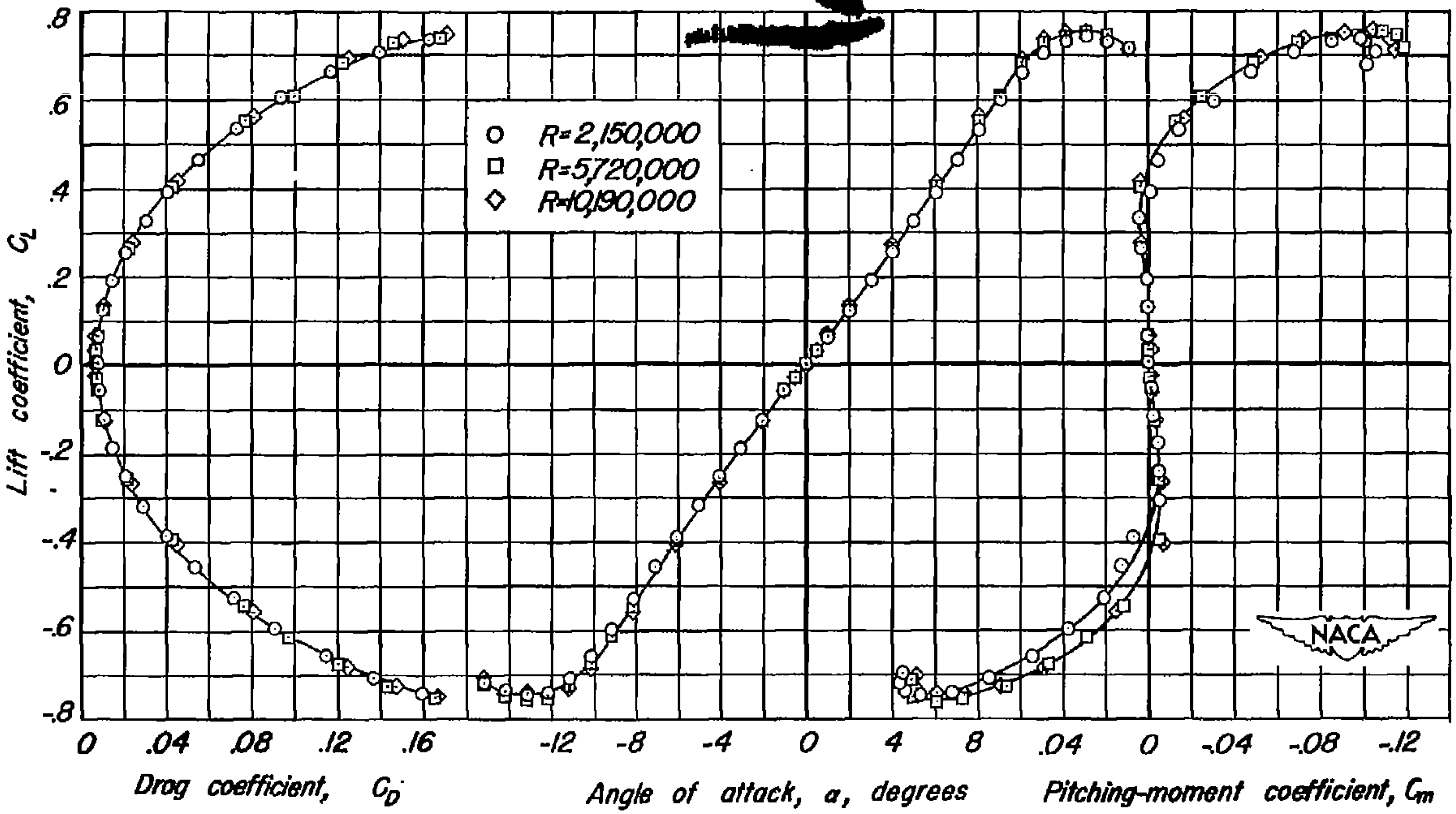

Figure 5.- The effect of Reynolds number on the aerodynamic characteristics of the wing with the sharp ridge profile. M, 0.20.

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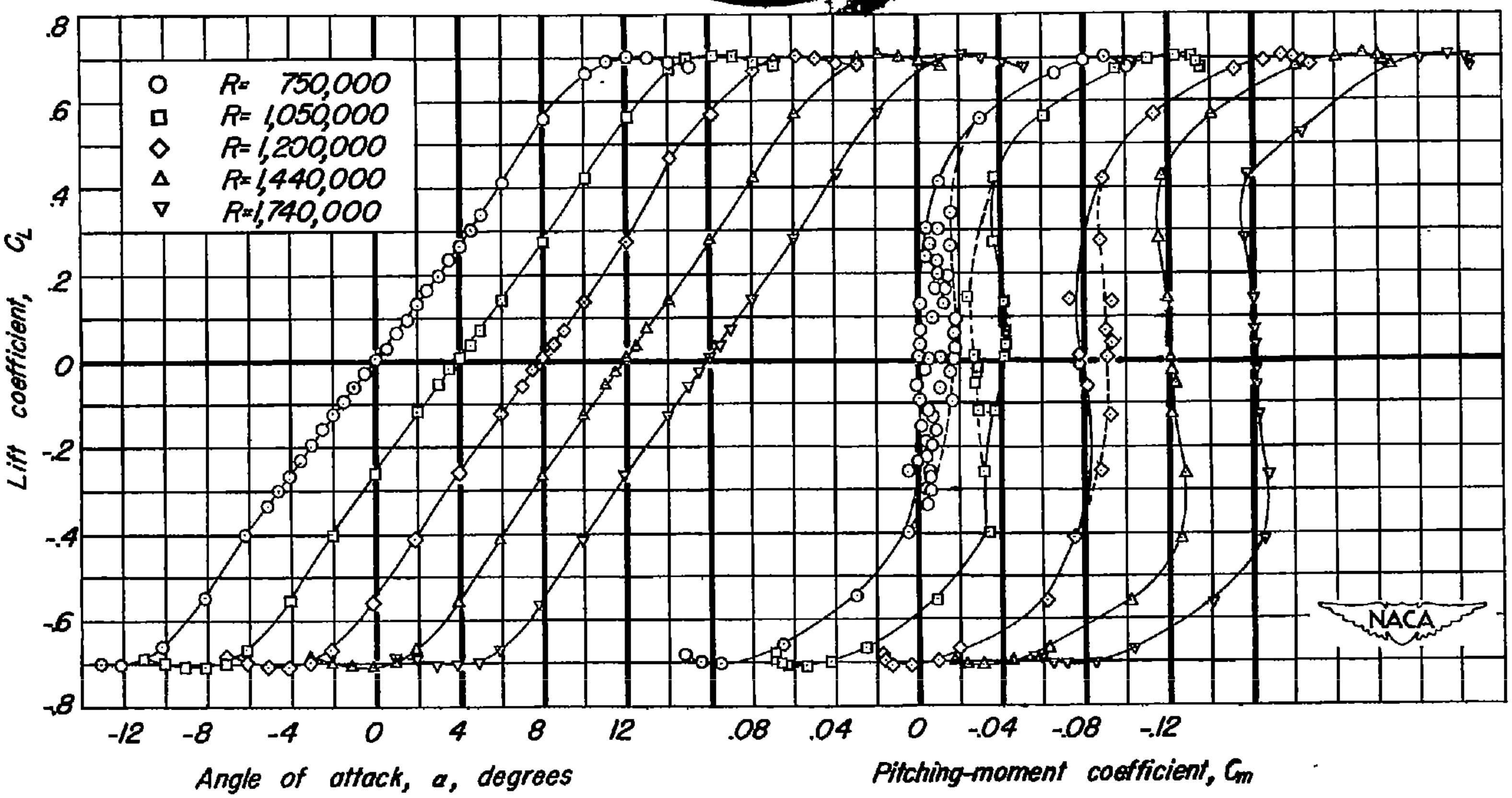

Figure 6.- The effect of Reynolds number on the aerodynamic characteristics of the wing with the sharp ridge profile. M, 0.50.

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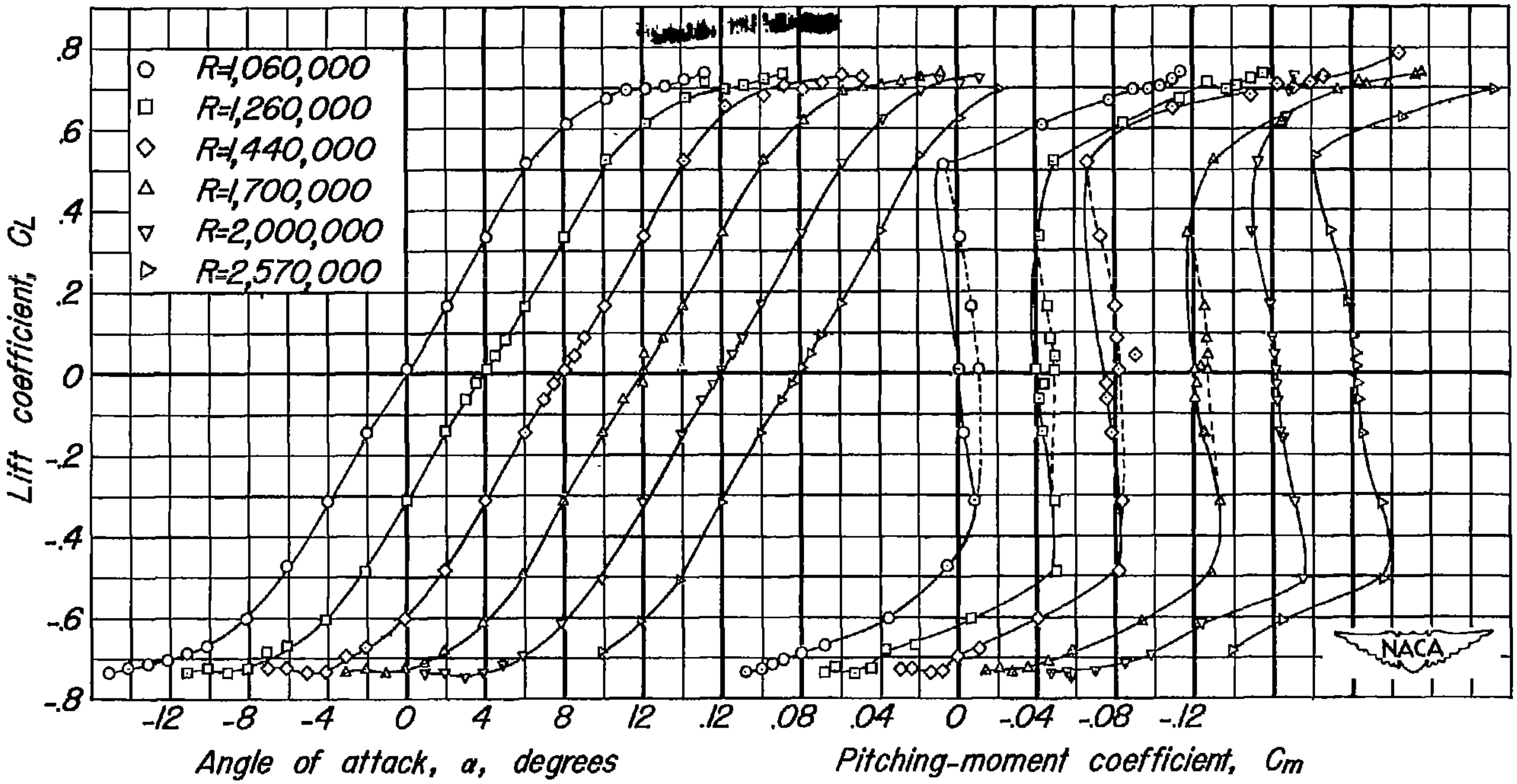

Figure 7.-The effect of Reynolds number on the aerodynamic characteristics of the wing with the sharp ridge profile. M, 0.80.

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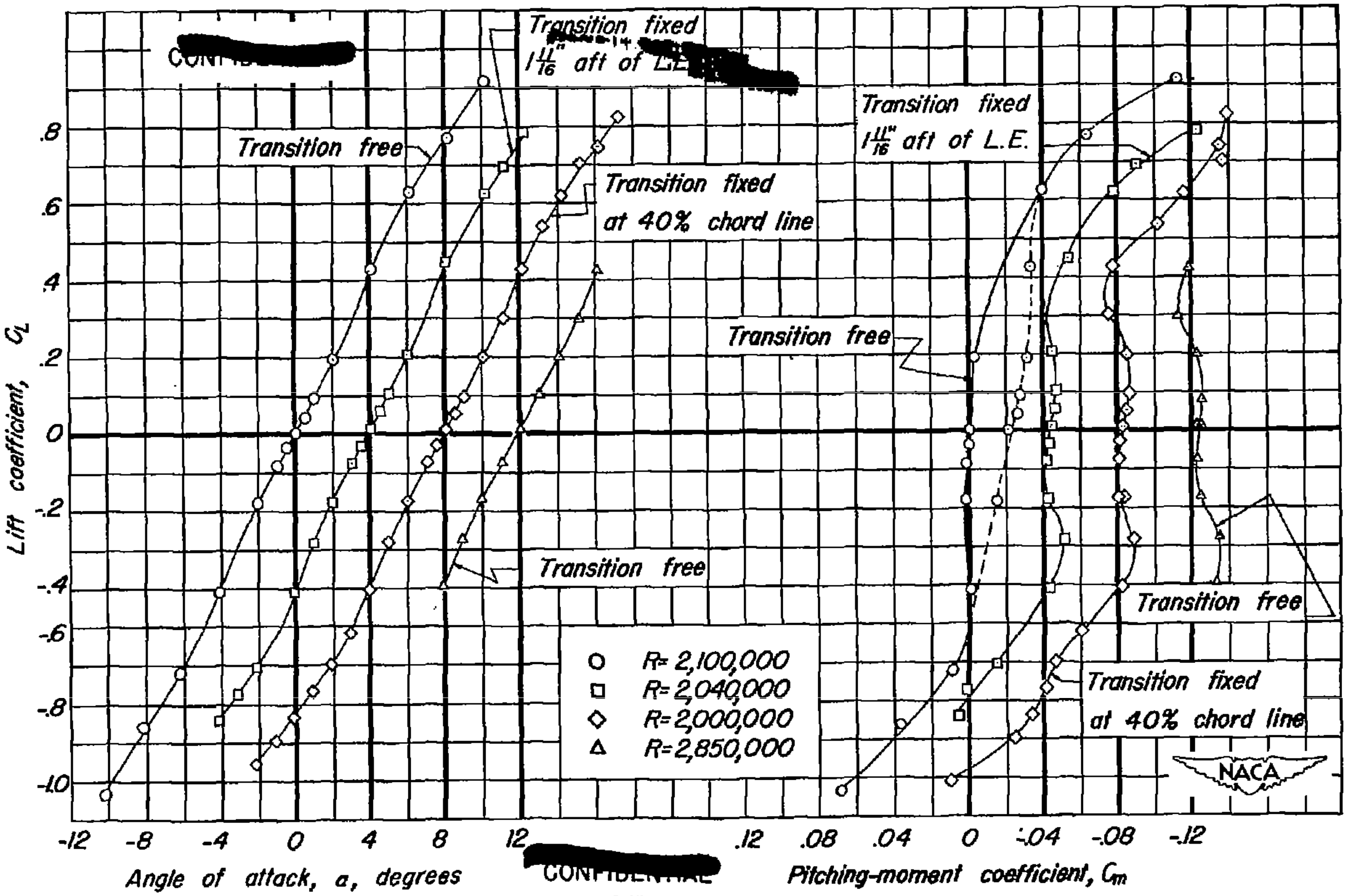

Figure 8.- The effect of fixed transition [redacted] number on the aerodynamic characteristics of the wing with the sharp ridge profile. M, 0.90.

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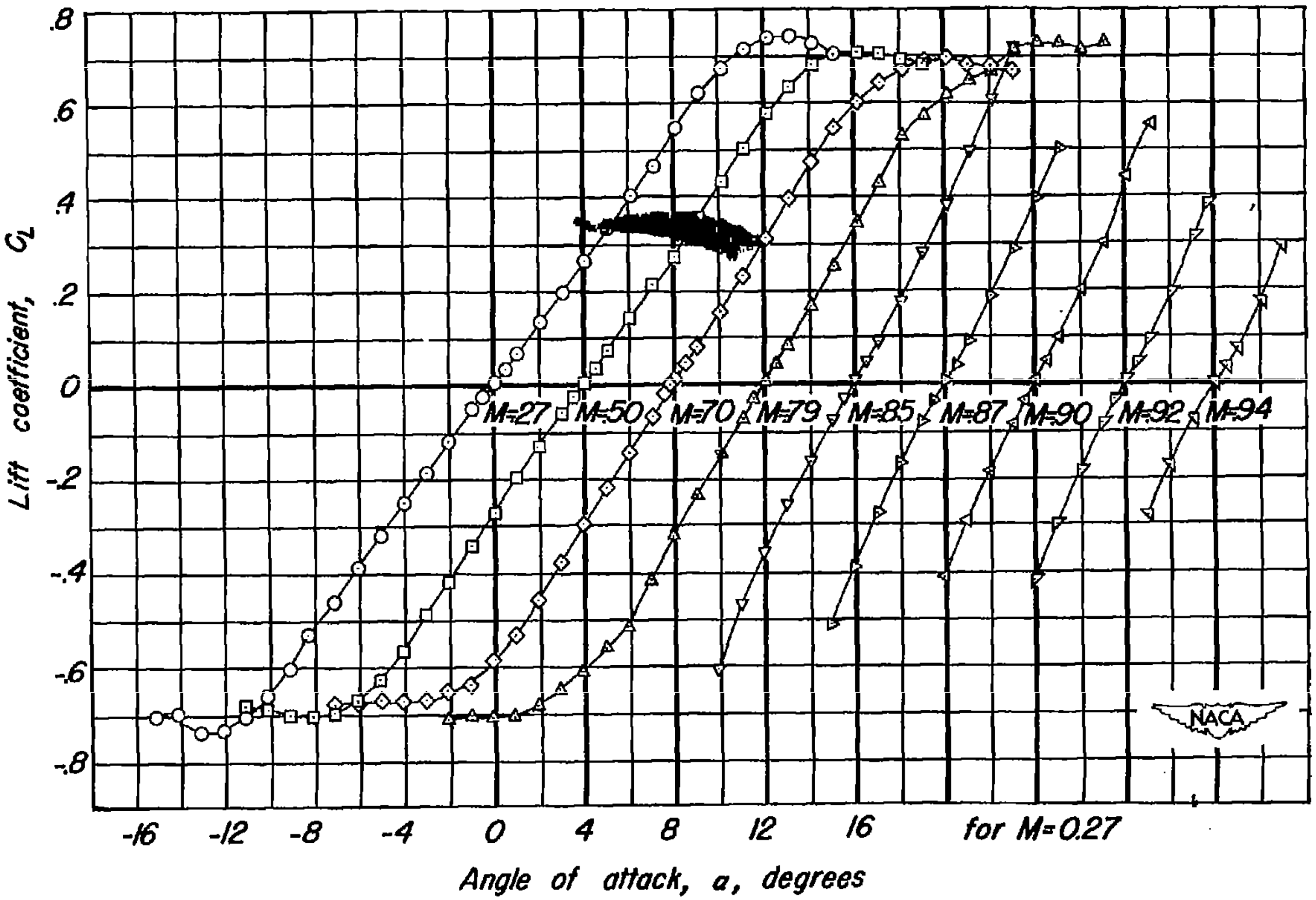

(a) C_L vs α

Figure 9.-The effect of Mach number [redacted] the aerodynamic characteristics of the wing with the round ridge profile. R, 2,730,000.

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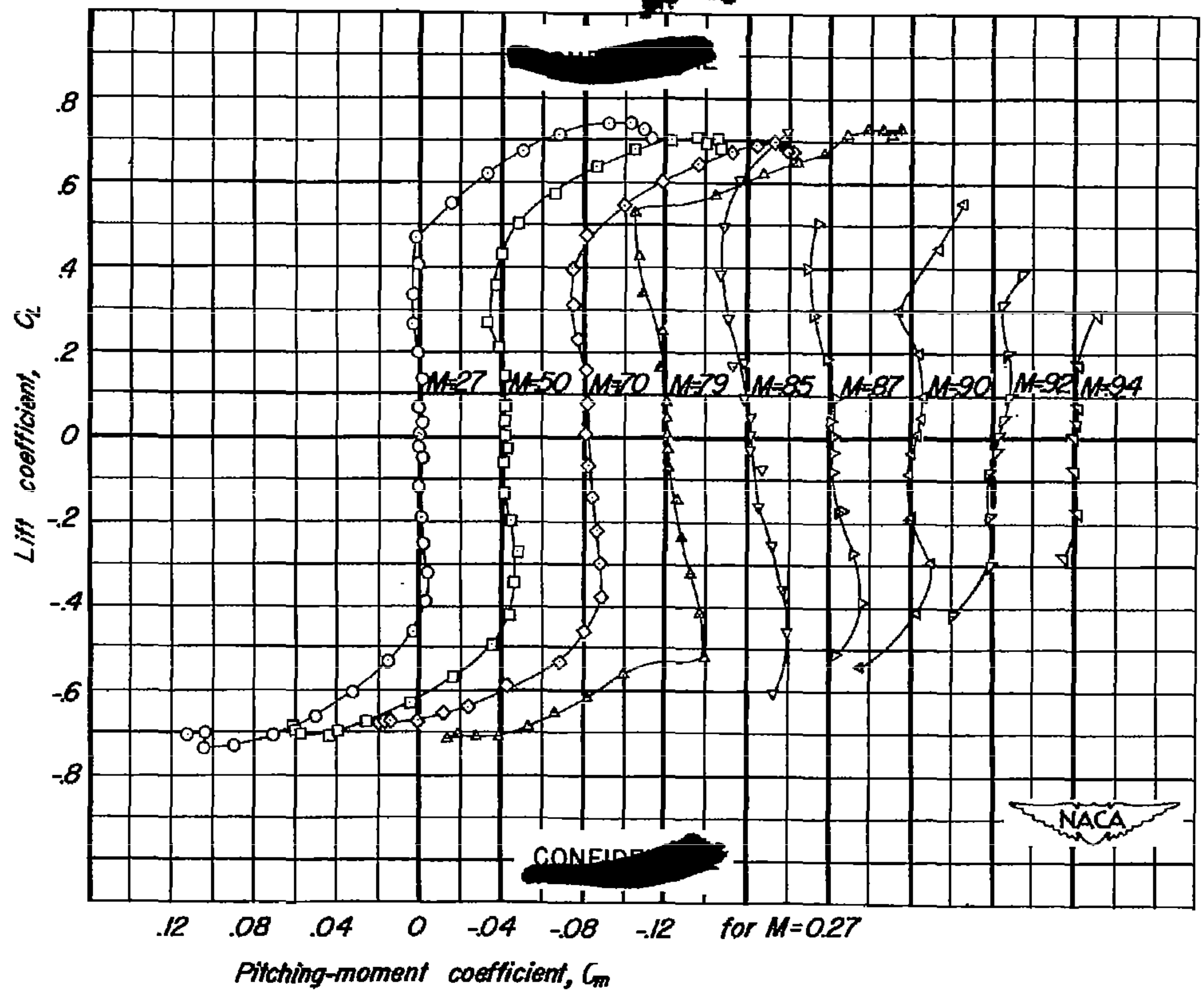

(b) C_m v C_L

Figure 9.-Continued.

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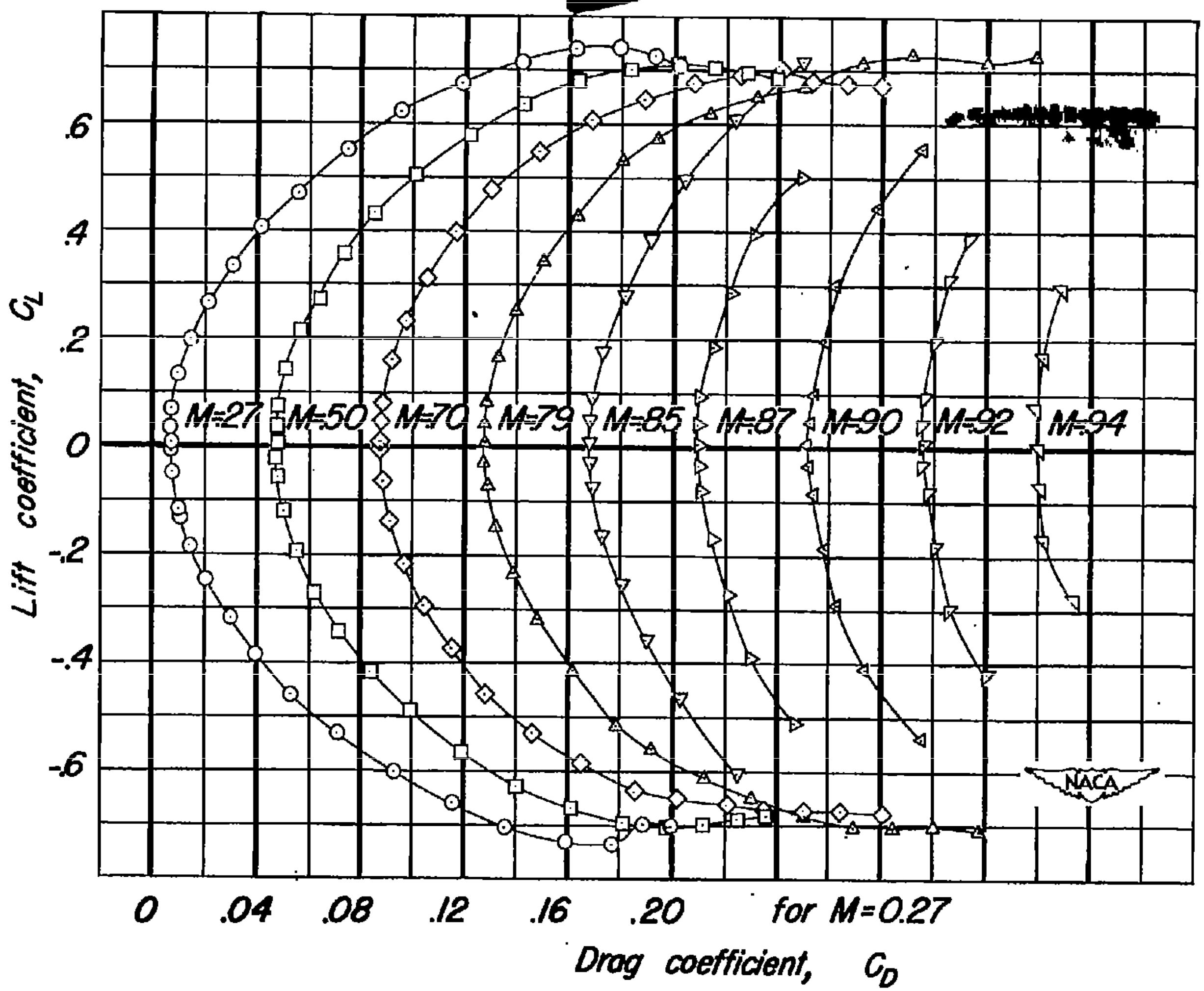

(c) C_D vs C_L

Figure 9.-Concluded.

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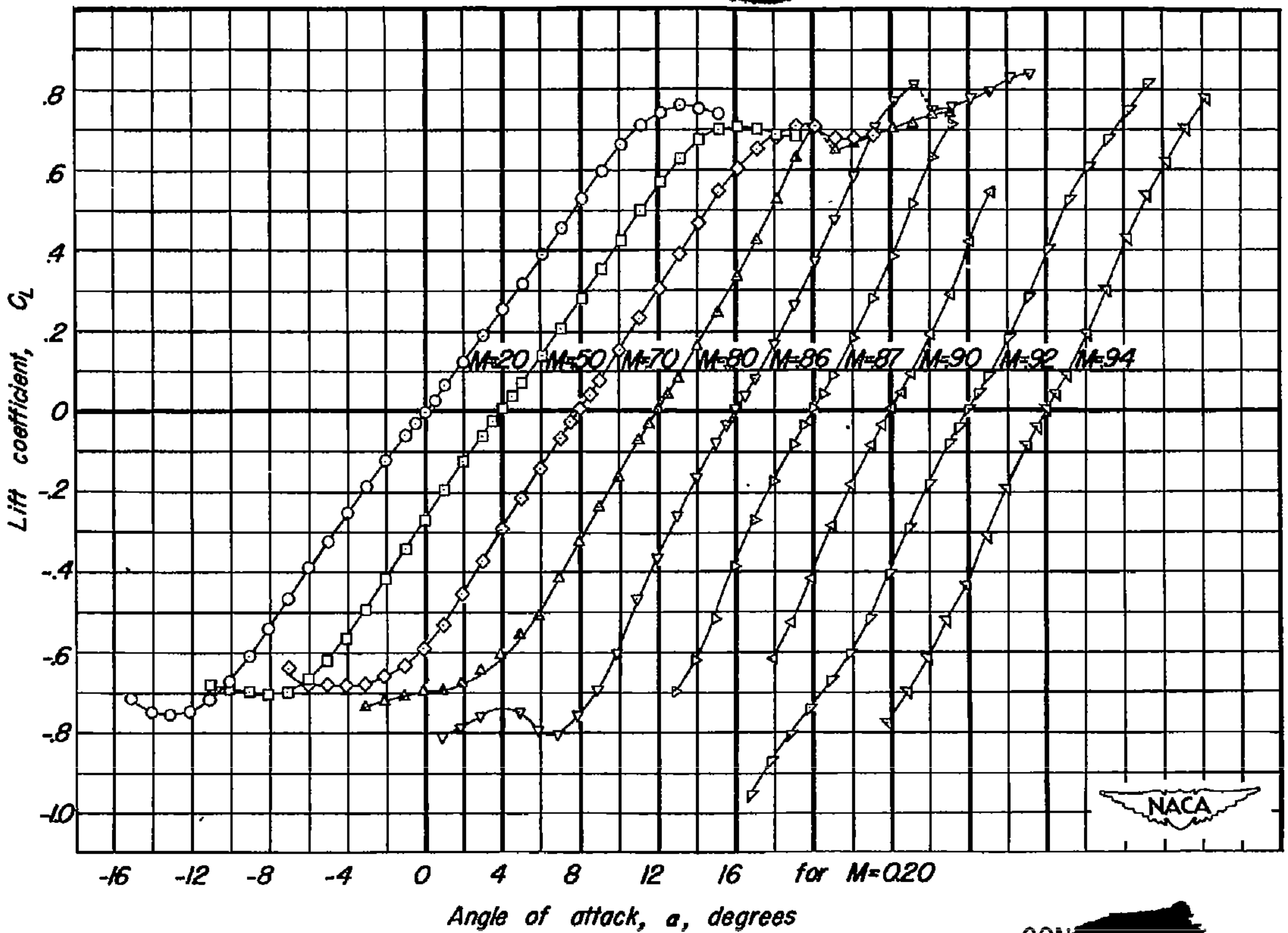

(a) C_L vs α

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Figure 10.- The effect of Mach number on the aerodynamic characteristics of the wing with the round ridge profile. R, 2,000,000.

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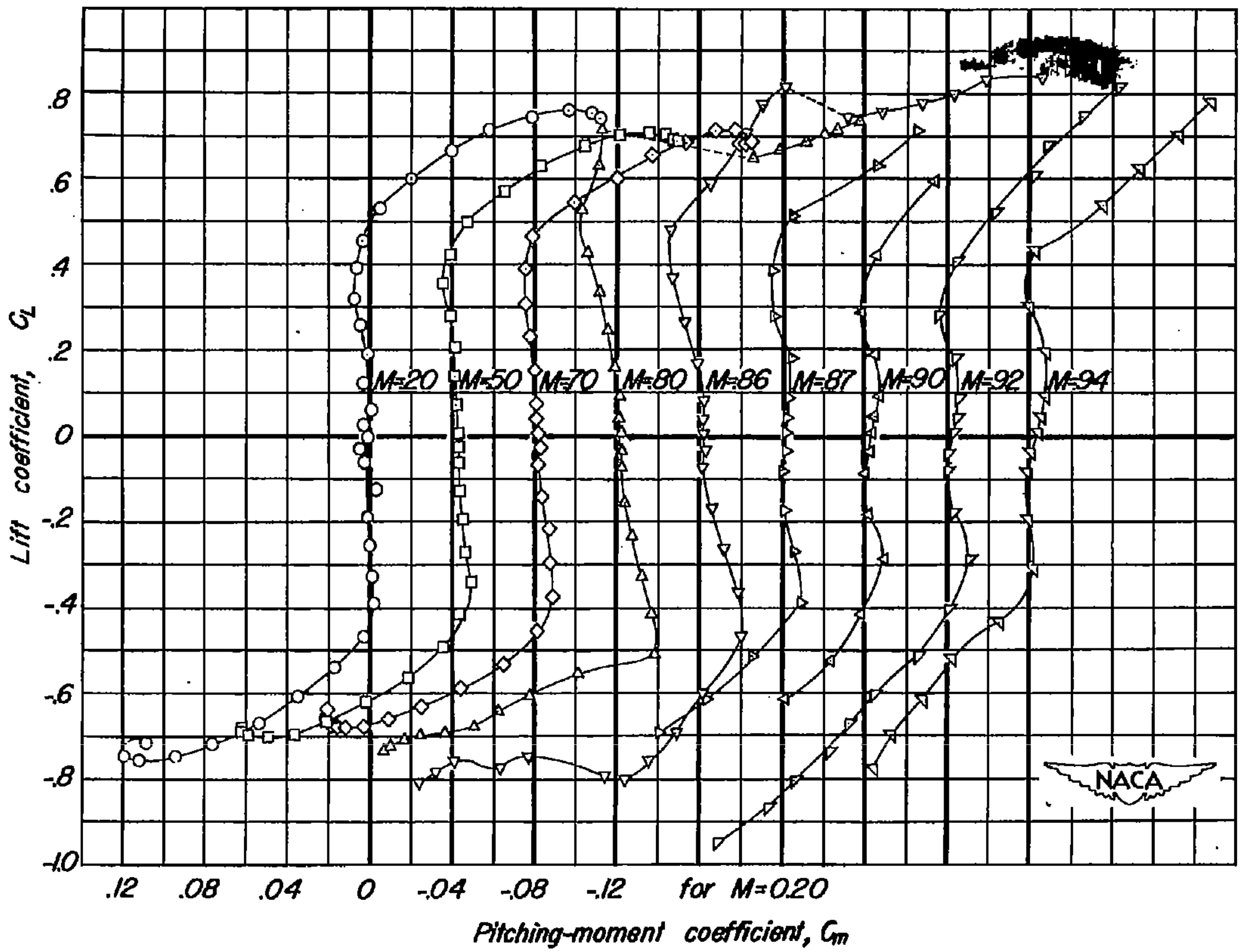

(b) C_m vs C_L

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Figure 10.-Continued.

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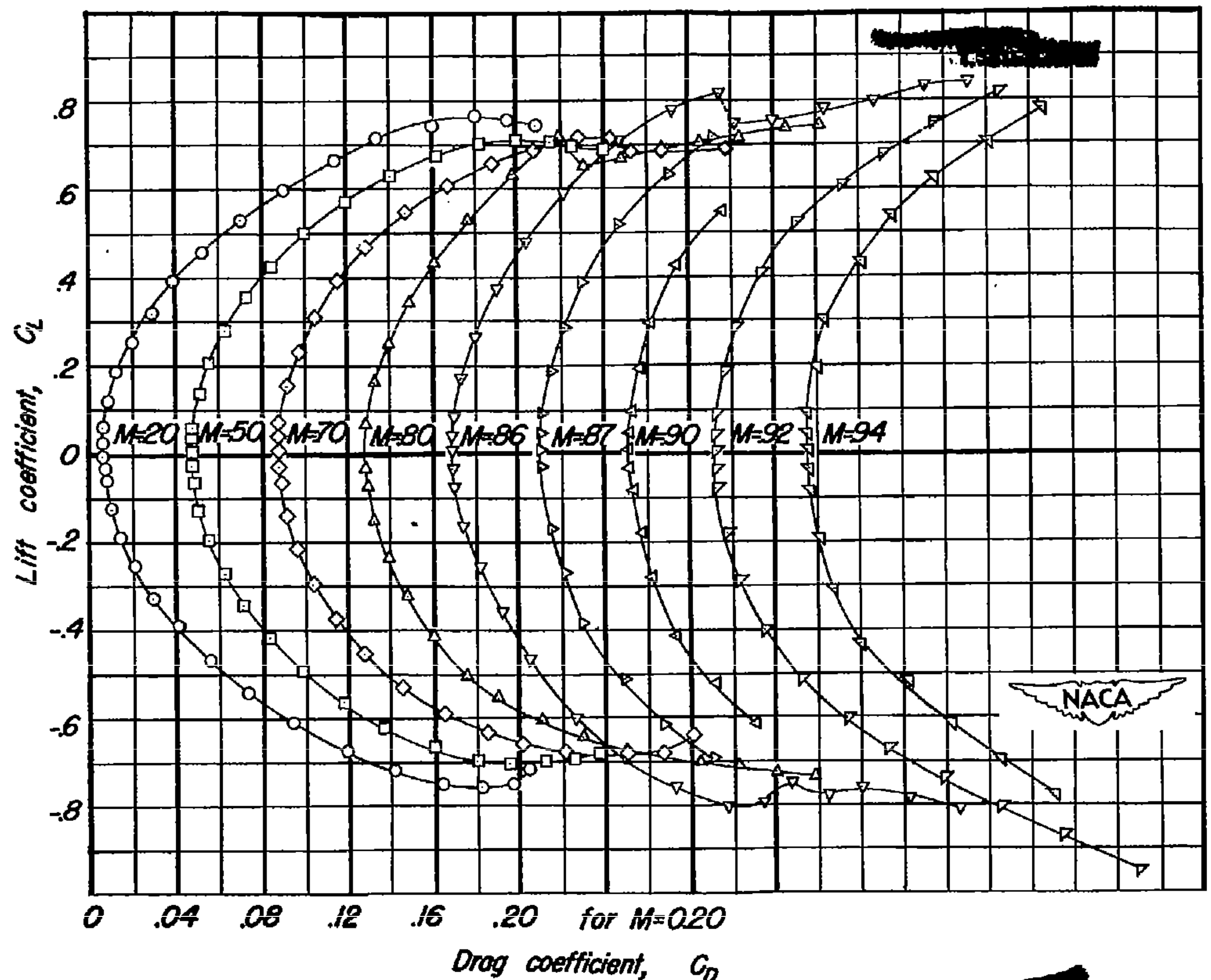

(c) C_D vs C_L

Figure 10.-Concluded.

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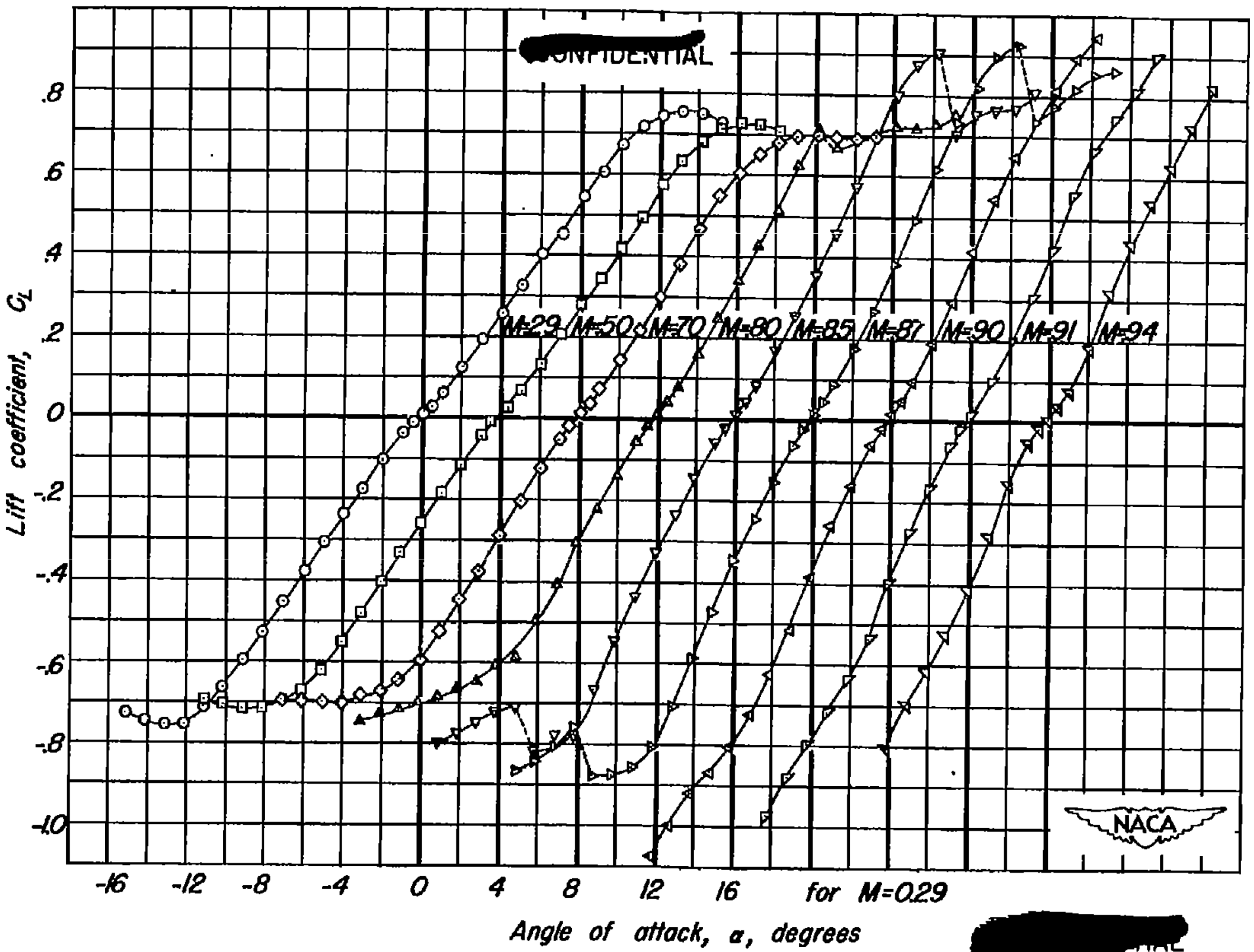

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(a) C_L vs α

Figure 11.- The effect of Mach number on the aerodynamic characteristics of the wing with round ridge profile. R, 1,000,000. All gaps sealed.

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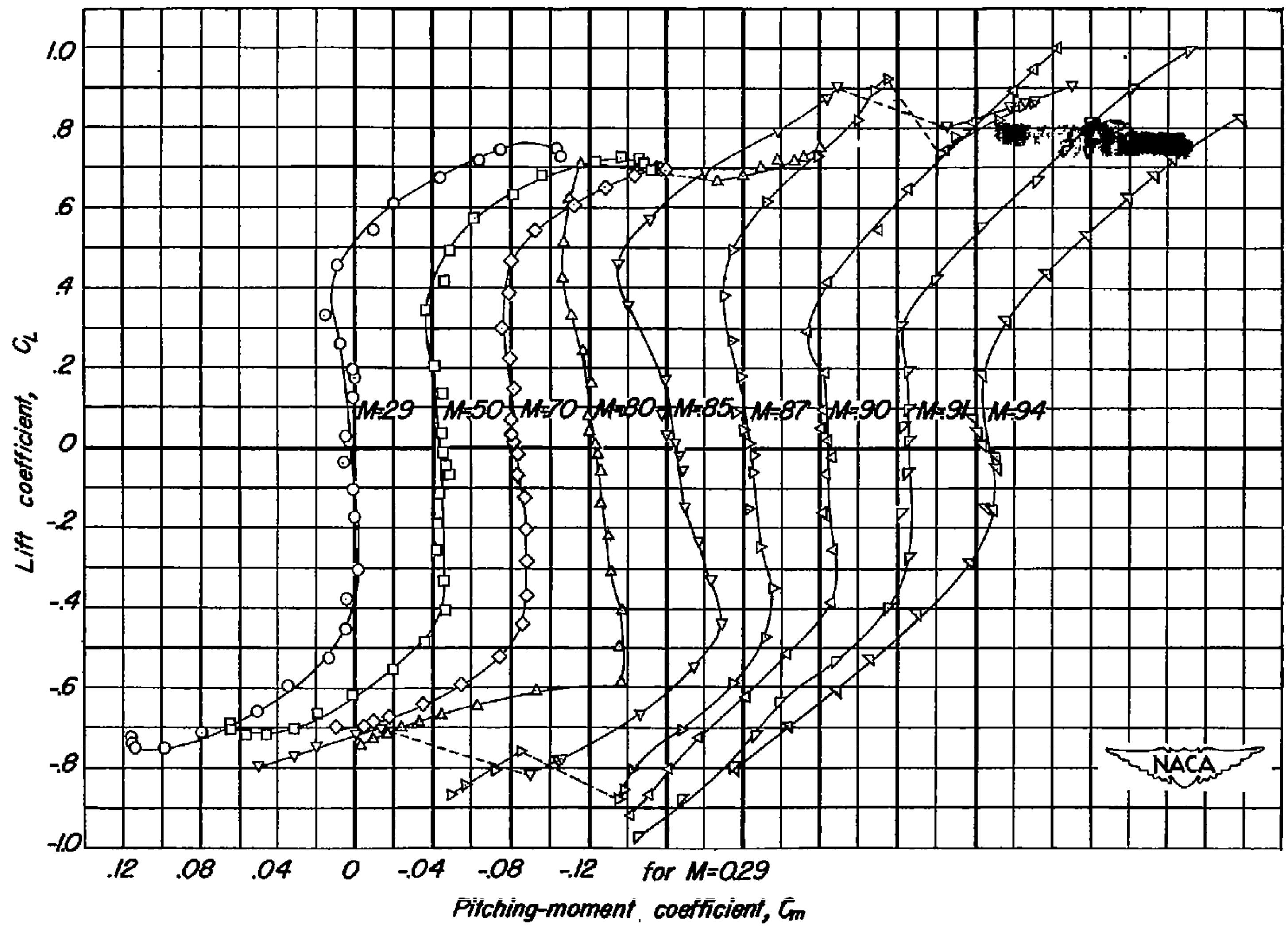

(b) C_m vs C_L

Figure 11.-Continued.

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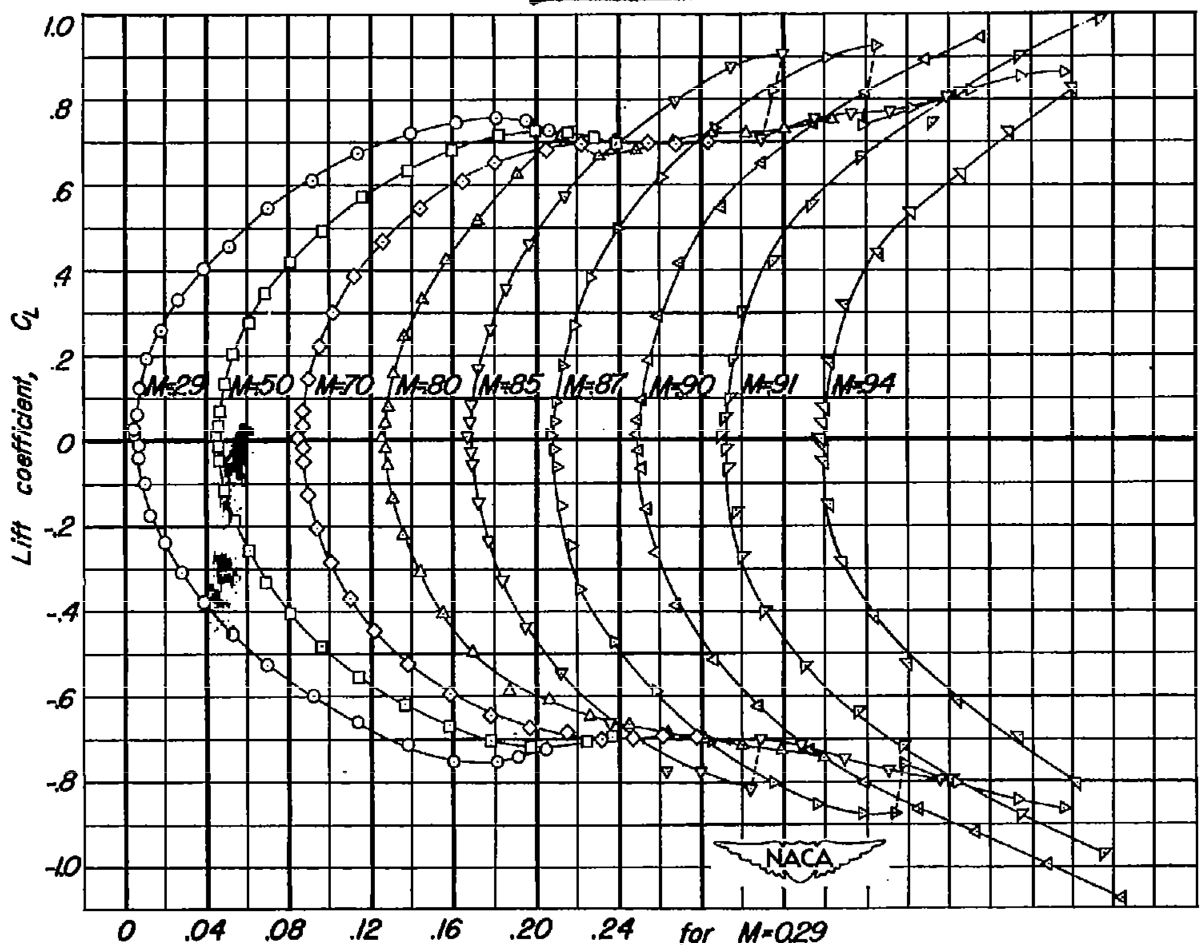

(c) C_D vs C_L

Figure 11.-Concluded.

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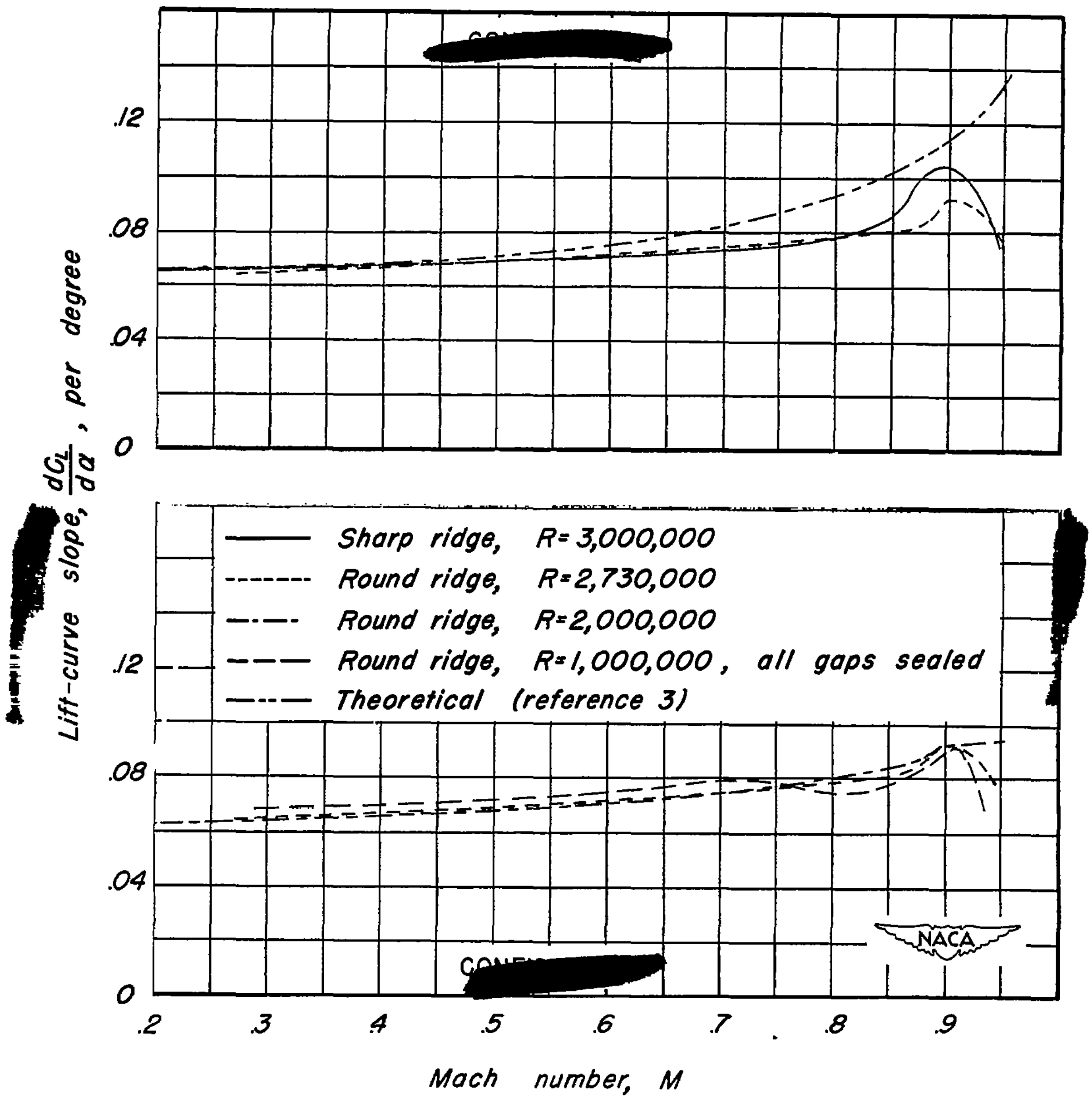

Figure 12.- The variation of lift–curve slope at zero lift with Mach number.

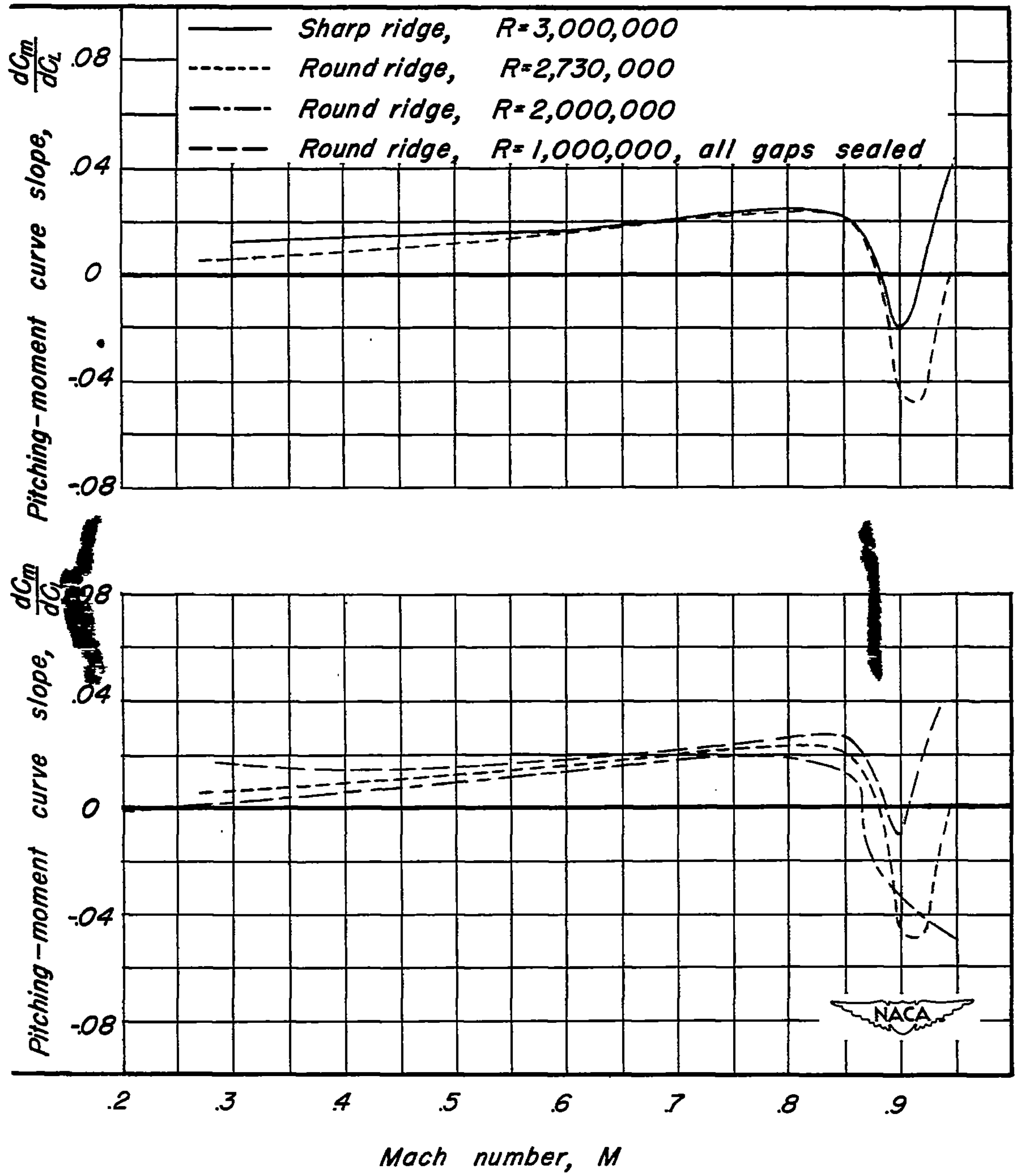

Figure 13.-The variation of pitching-moment-curve slope at zero lift with Mach number.

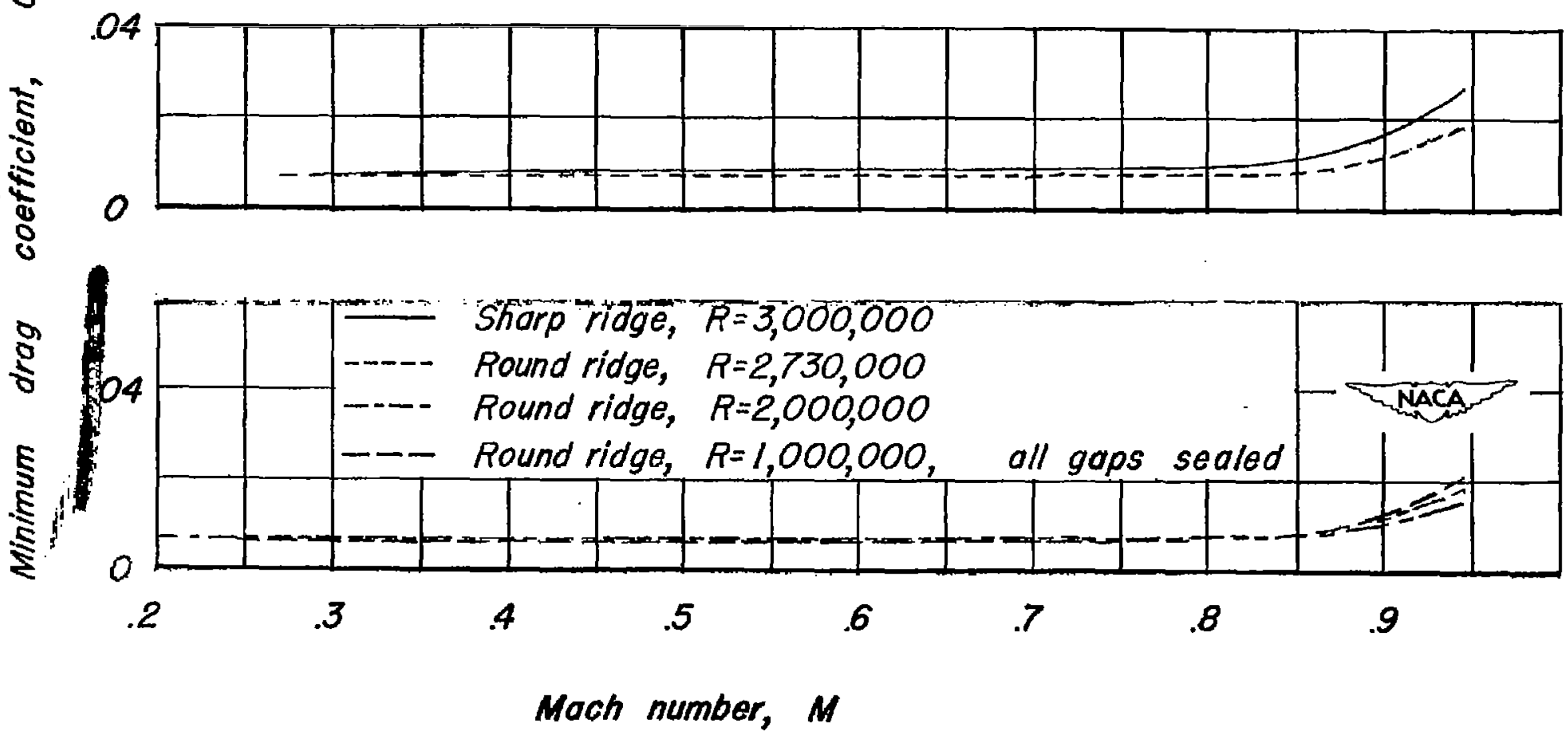

Figure 14.- The variation of minimum drag coefficient with Mach number.

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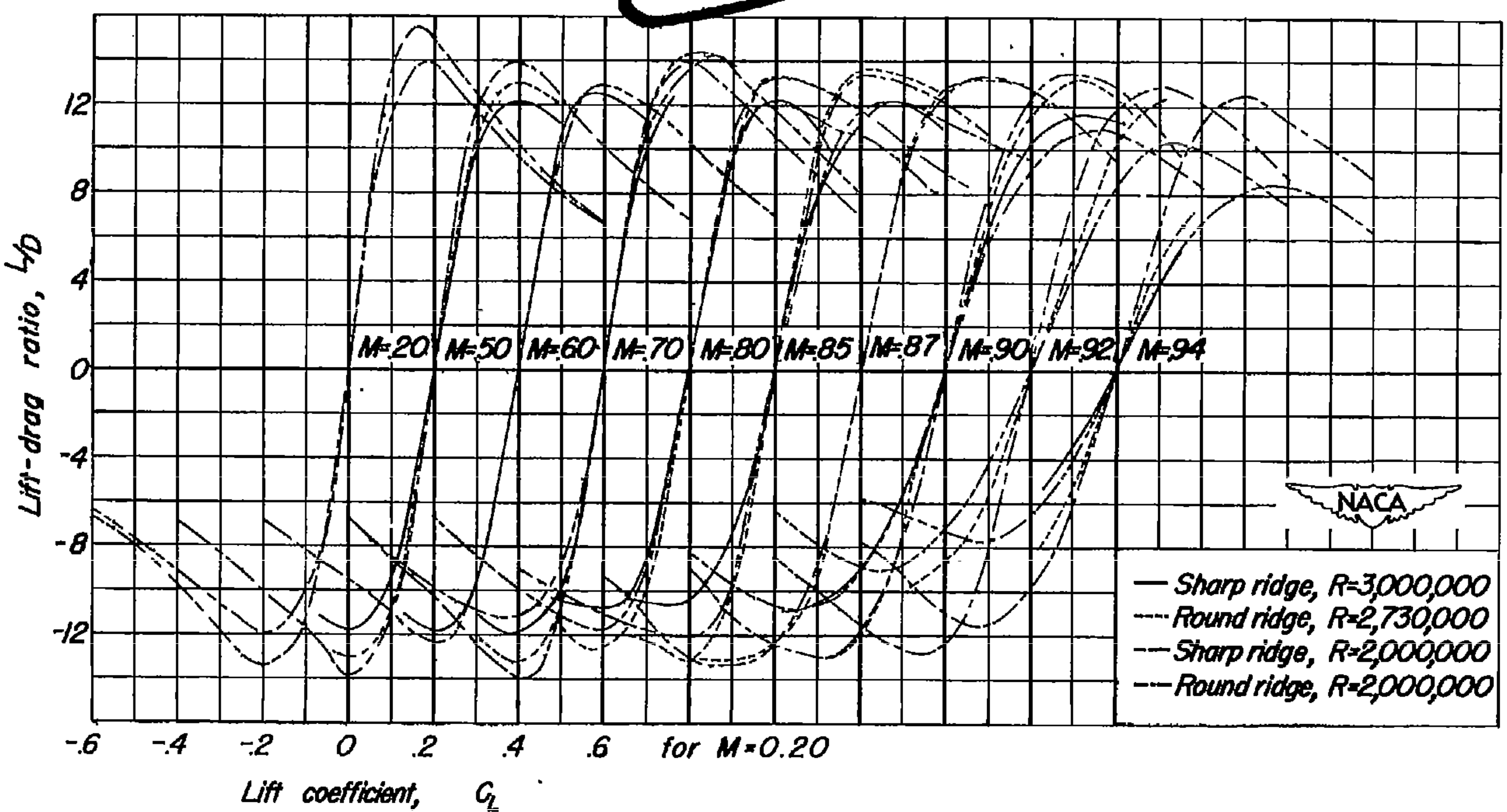

Figure 15.- The effect of section profile on the lift-drag ratio.

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